MODIS, VIIRS, Landsat, and SeaWiFS Pre-launch and On-orbit Calibration Experience, and Lessons Learned for CLARREO

Jack Xiong, Jim Butler, Brian Markham, Chuck McClain ,and Steve Platnick

Sciences and Exploration Directorate, NASA/GSFC

Greenbelt, MD 20771

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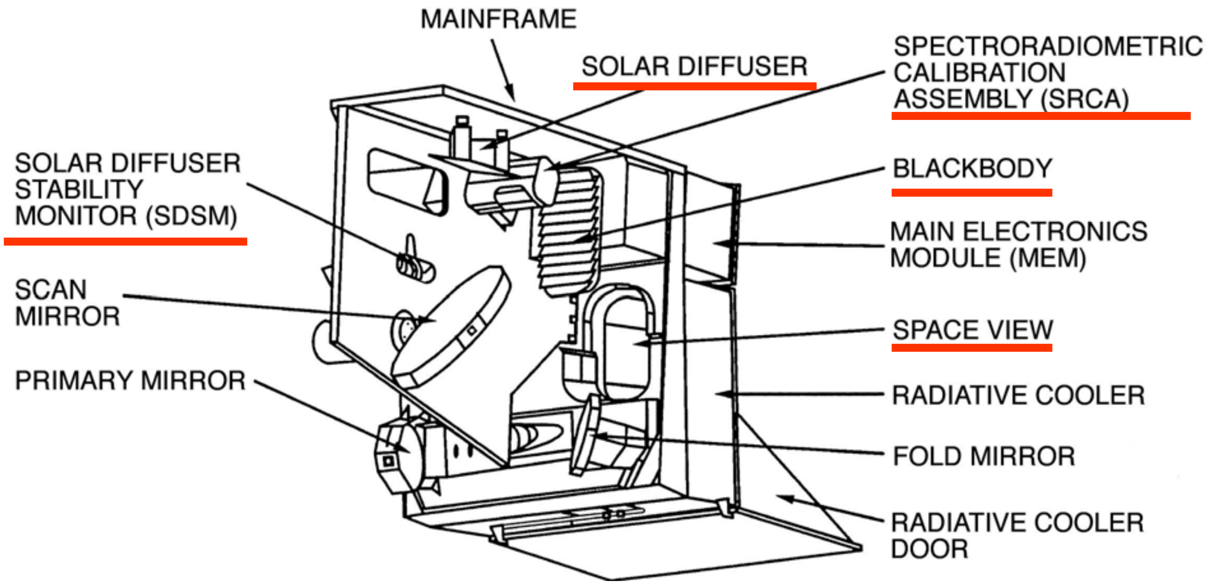
Outline

- Instrument Background
- Instrument Calibration and Characterization
  - MODIS
  - VIIRS
  - Landsat-7 ETM+
  - SeaWiFS
- Lessons Learned
- CLARREO: A Calibration Benchmark for Future Earth Observing Missions
- Summary

MODIS Instrument



Terra

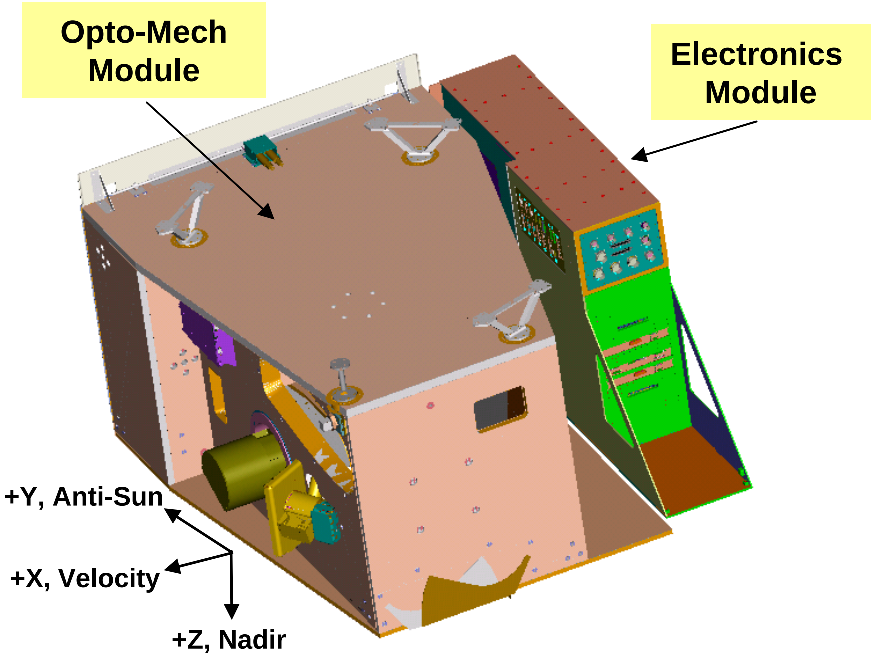
Aqua

- 20 Reflective solar bands (RSB): 0.41-2.2μm
- 16 Thermal emissive bands (TEB): 3.7-14.4μm
- 3 spatial resolutions at nadir: 250m, 500m and 1000m
- 4 Focal Plane Assemblies (FPA): VIS, NIR, SMIR, LWIR
- 5 On-Board Calibrators: SD, SDSM, SRCA, BB, and SV port

- Two MODIS (Terra and Aqua): Complementary morning and afternoon observations
- A broad range of applications: land, oceans, and atmosphere

VIIRS Instrument

- **Multi-spectral crosstrack scanning instrument**
  - Rotating telescope
  - Half angle mirror (HAM) for de-rotation
- **Imagery and radiometry**
  - “Fine” (imaging) 0.4km resolution (nadir)
  - “Moderate” (radiometry) 0.8km resolution
- **22 spectral bands (0.4–12.5µm)**
  - 15 “reflective” VNIR-SWIR bands 0.4-2.3µm
  - 3 “mixed” MWIR bands 3.5 -4.1µm
  - 4 “emissive” LWIR bands 8.4-12.5µm
  - Automatic dual VNIR & triple DNB gains
- **EDR-dependent swath widths**
  - 1700, 2000, and 3000 km



Launch: Jan. 2011

Heritage Sensors: MODIS, SeaWiFS, THEMIS, TRMM VIRS, ETM+

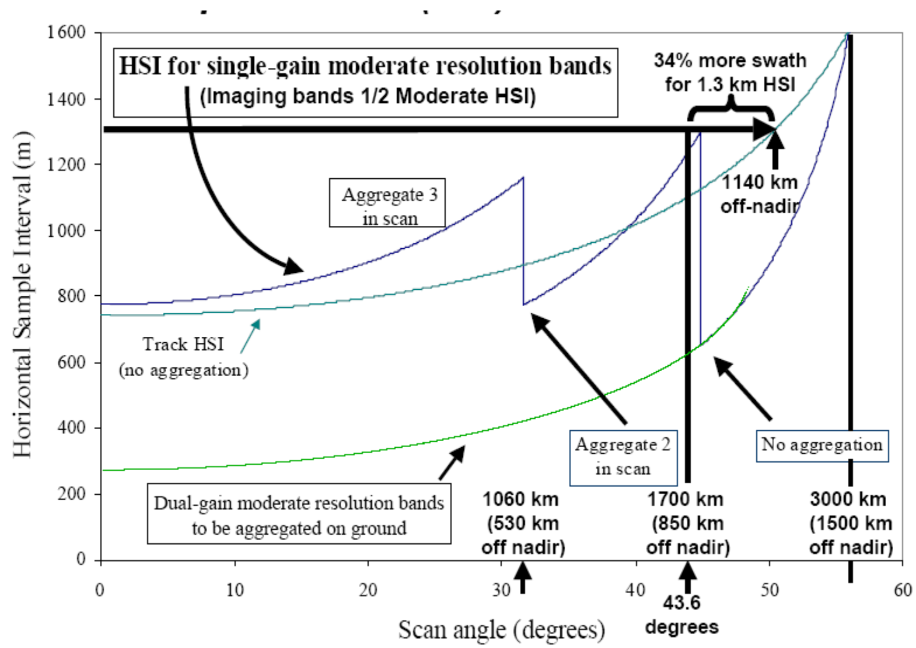
MODIS and VIIRS

VIIRS Band	Spectral Range (um)	Nadir HSR (m)	MODIS Band(s)	Range	HSR
DNB	0.500 - 0.900				
○ M1	0.402 - 0.422	750	8	0.405 - 0.420	1000
○ M2	0.436 - 0.454	750	9	0.438 - 0.448	1000
○ M3	0.478 - 0.498	750	3 10	0.459 - 0.479 0.483 - 0.493	500 1000
○ M4	0.545 - 0.565	750	4 or 12	0.545 - 0.565 0.546 - 0.556	500 1000
I1	0.600 - 0.680	375	1	0.620 - 0.670	250
○ M5	0.662 - 0.682	750	13 or 14	0.662 - 0.672 0.673 - 0.683	1000 1000
M6	0.739 - 0.754	750	15	0.743 - 0.753	1000
I2	0.846 - 0.885	375	2	0.841 - 0.876	250
○ M7	0.846 - 0.885	750	16 or 2	0.862 - 0.877 0.841 - 0.876	1000 250
M8	1.230 - 1.250	750	5	SAME	500
M9	1.371 - 1.386	750	26	1.360 - 1.390	1000
I3	1.580 - 1.640	375	6	1.628 - 1.652	500
M10	1.580 - 1.640	750	6	1.628 - 1.652	500
M11	2.225 - 2.275	750	7	2.105 - 2.155	500
I4	3.550 - 3.930	375	20	3.660 - 3.840	1000
M12	3.660 - 3.840	750	20	SAME	1000
○ M13	3.973 - 4.128	750	21 or 22	3.929 - 3.989 3.929 - 3.989	1000 1000
M14	8.400 - 8.700	750	29	SAME	1000
M15	10.263 - 11.263	750	31	10.780 - 11.280	1000
I5	10.500 - 12.400	375	31 or 32	10.780 - 11.280 11.770 - 12.270	1000 1000
M16	11.538 - 12.488	750	32	11.770 - 12.270	1000

○ **Dual gain band**

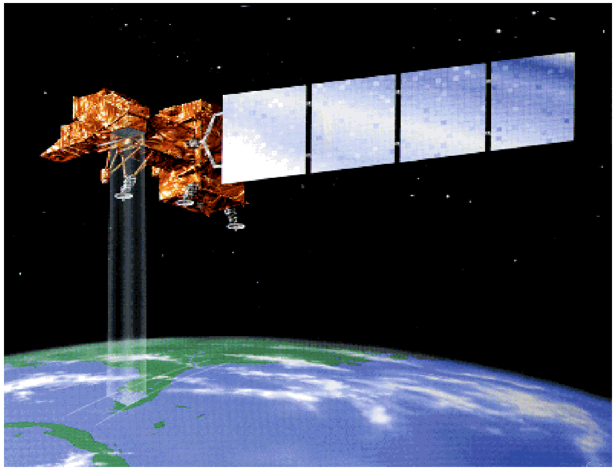
Changes from MODIS

- Use of a Telescope instead of rotating mirror
- Use of dual gain bands
- Removed CO2 bands
- Deleted Spectro-Radiometric Assembly
- Added pixel aggregation
- Guaranteed End-Of-Life Performance Spec
- Solar Diffuser Screen with Earthshine shade



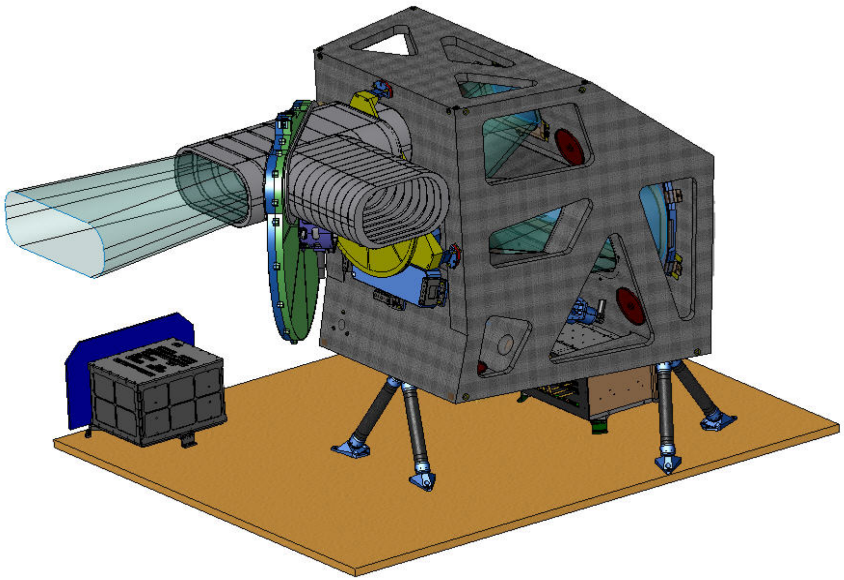
Landsat-7 ETM+

- Landsat-7 launched 4/15/99
  - 705km 10:00AM descending
- Whiskbroom scanner - 8 bit
- 8 spectral bands
  - 4 VNIR (30 meters)
  - 2 SWIR (30 meters)
  - 1 TIR (60 meters)
  - 1 Panchromatic (15 meters)
- On-board calibrators
  - Diffuser (FASC)
  - Internal calibrator
    - Shutter
    - Lamps
    - Blackbody
- 185 km swath; 16 day repeat



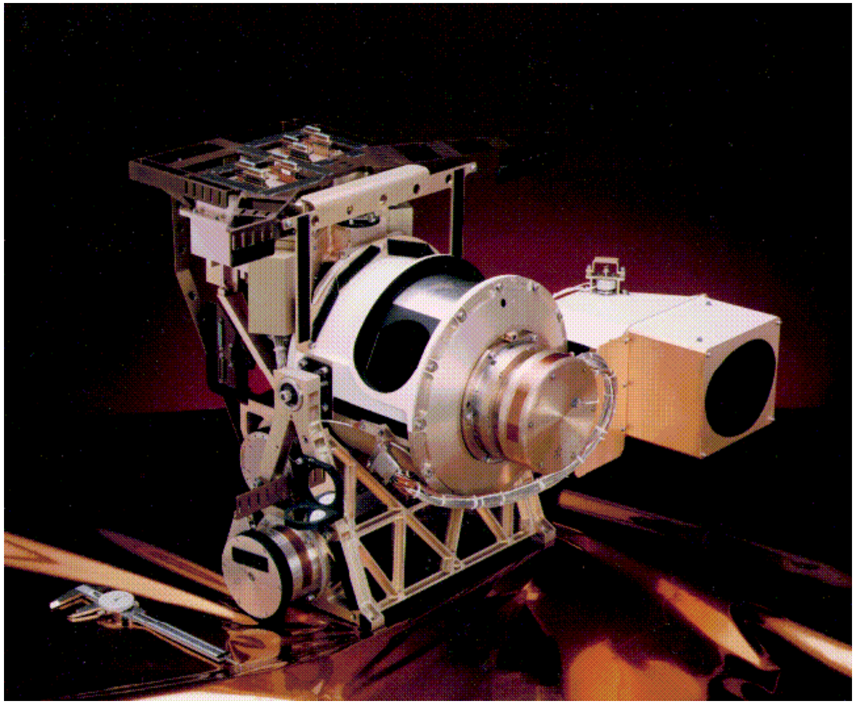
Landsat Data Continuity Mission OLI

- Dec 2012 launch
- Pushbroom - 12 bit
- 9 spectral bands
  - 5 VNIR (30 meters)
  - 2 SWIR (30 meters)
  - 1 Cirrus detection (30 meters)
  - 1 Panchromatic (15 meters)
- On-board calibrators
  - Diffuser
    - Working
    - Pristine
  - Internal lamps - 3 pairs
  - Shutter



SeaWiFS Instrument

- September 1997 to present
- Orbit: Noontime, sun-synchronous descending
- Instrument Components & Spectral Bands;
  - Fore optics: rotating telescope
  - 8 wavelengths from 412 to 865 nm
  - 4 detectors/bands in TDI w/ bilinear gains
  - 4 commandable gain settings
  - Depolarizer: polarization sensitivity ~0.25%
  - 10 bit digitization
- Spatial Resolution
  - 1.1 km local area coverage
    - Swath: 2800 km
  - 4.4 km global area coverage
- Swath 1500 km



Instrument Calibration and Characterization

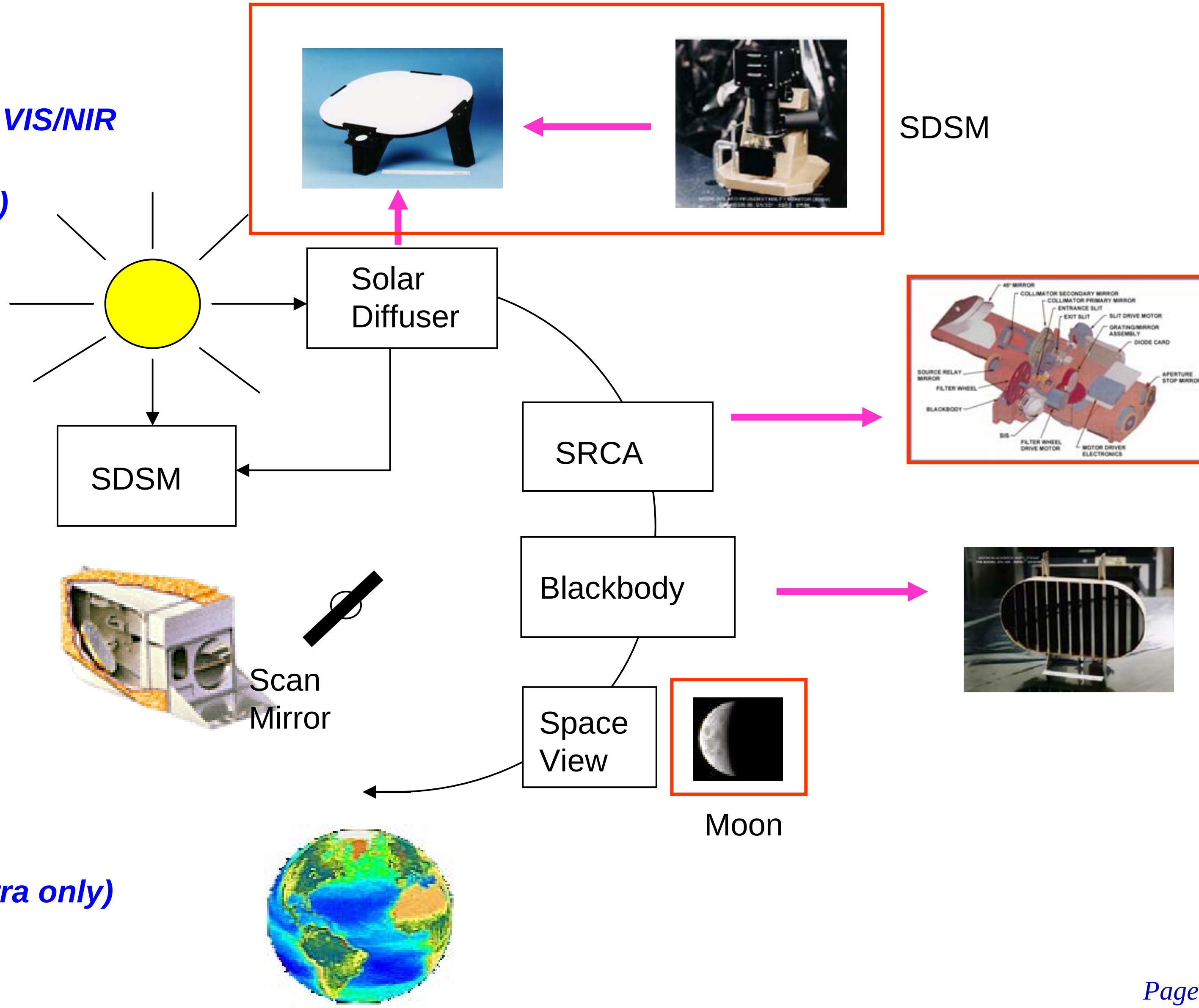
- MODIS, (VIIRS), Landsat, SeaWiFS
- VIS and NIR
  - Radiometric Calibration Activities
- Pre-launch and On-orbit Calibration
  - Approaches and Traceability

MODIS Pre-launch Calibration

- Radiometric
  - Calibration source: SIS-100 (NIST traceable) at multiple radiance levels (lamp configurations)
  - Calibration parameters: gain, nonlinearity, SNR, dynamic range, gain dependence on the instrument temperatures
  - Three instrument temperatures for thermal vacuum test
  - Primary and redundant electronics
  - Solar diffuser BRDF calibration (NIST traceable)
- Others (all system level)
  - Spectral: relative spectral response (RSR)
  - Spatial: pointing, band-to-band registration (BBR)
  - Response versus scan angle (RVS)
  - Polarization sensitivity

MODIS On-orbit Calibration

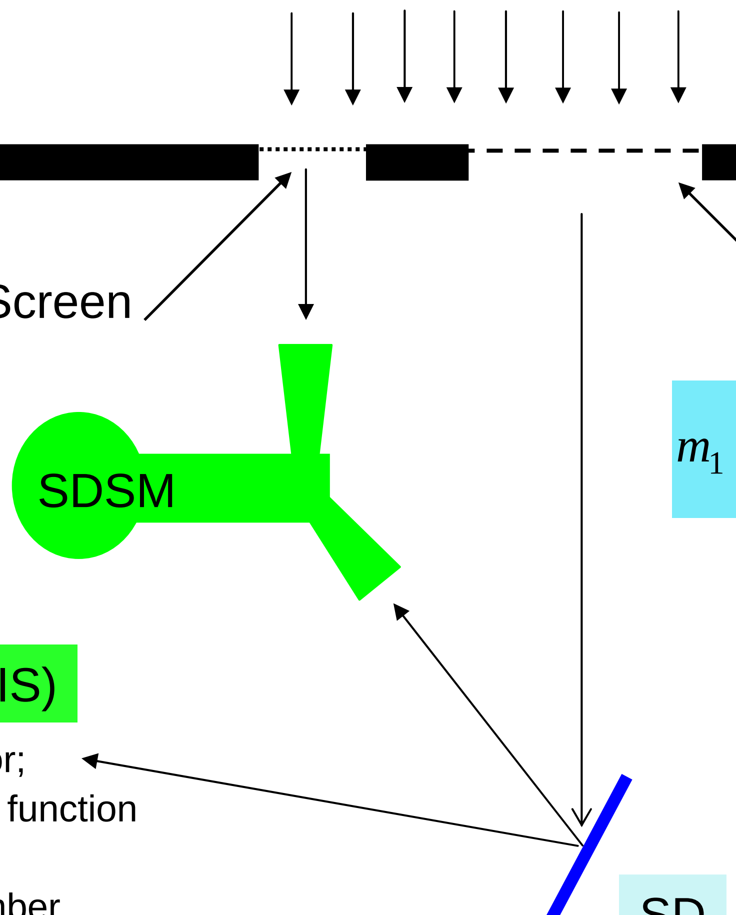
Quarterly BB for IR
Bi-weekly SD/SDSM for VIS/NIR
Regular SRCA 3 modes
(spat, spec, radiometric)



Spacecraft maneuvers:
Yaw, roll, and pitch (Terra only)
Lunar observations

SD/SDSM Calibration

Reflectance Factor $\rho_{EV}\cdot\cos(\theta_{EV}) = m_1\cdot dn^*_{EV}\cdot d^2_{Earth-Sun}$



$$m_1 = \frac{BRF_{SD}\cdot\cos(\theta_{SD})}{< dn^*_{SD} > \cdot d^2_{Earth-Sun}}\cdot\Gamma_{SD}\cdot\Delta_{SD}$$

$$\Delta_{SD} = \frac{\overline{dc_{SD}}}{\overline{dc_{Sun}}}$$

Scan Mirror (MODIS)

Δ_{SD}: SD degradation factor;

Γ_{SD}: SD screen vignetting function

d: Earth-Sun distance

dn*: Corrected digital number

dc: Digital count of SDSM

VIIRS Pre-launch and On-orbit Calibration

- Pre-launch calibration and characterization
  - Similar to MODIS (FU1 on NPP TV test scheduled for March/April 2009)
  - Ambient and most pre-TV tests completed
  - Experience and lessons from MODIS
    - Polarization characterization (PSA and polarization sheet)
    - SIS stability monitor

- On-orbit calibration and characterization
  - Similar to MODIS using SD/SDSM
    - SD observations with an attenuation screen every orbit
  - Monthly lunar observations via maneuvers (NPP/VIIRS)

Landsat-7 ETM+ Pre-launch Calibration

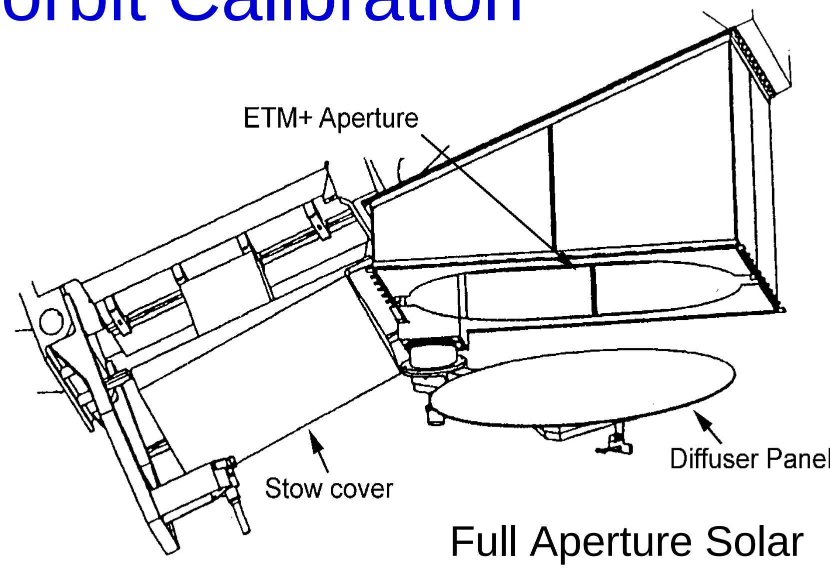
- Radiometric
  - Calibration source: SIS-100; SIS-48” (NIST traceable)

    Landsat Transfer Radiometer (VNIR monitor)
  - Three instrument temperatures for thermal vacuum test
  - Internal Lamp characterization; noise characterization
  - Solar diffuser BRDF calibration
- Others
  - Spectral: relative spectral response (RSR)

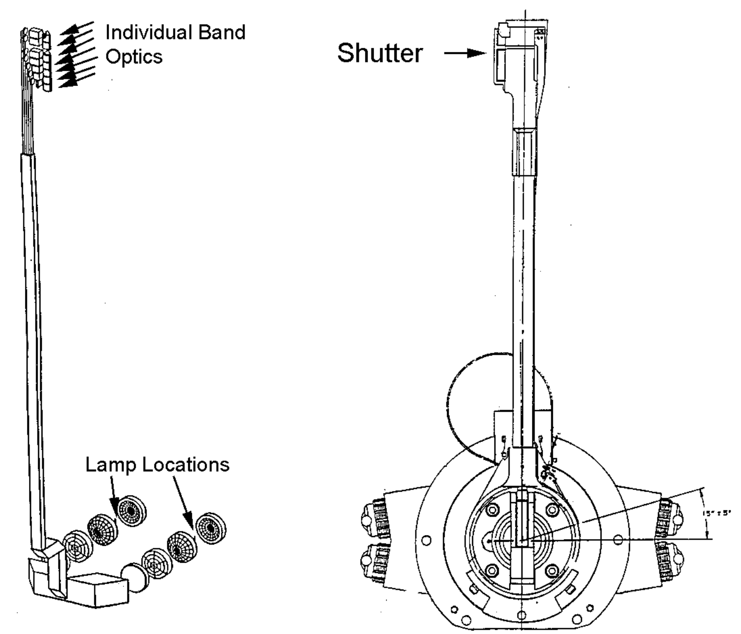
    Combination of component level measurements
  - Spatial: alignment, band-to-band registration (BBR), Modulation Transfer Function (MTF)

Landsat-7 ETM+ On-orbit Calibration

- Solar Diffuser measurements monthly
- Internal Calibrator (IC) measurements every scan
  - Shutter and primary lamp
  - Secondary lamp measurements ~monthly
- Vicarious measurements ~ monthly
- Desert (4 sites) measurements ~ 2/month



Full Aperture Solar Calibrator (FASC)



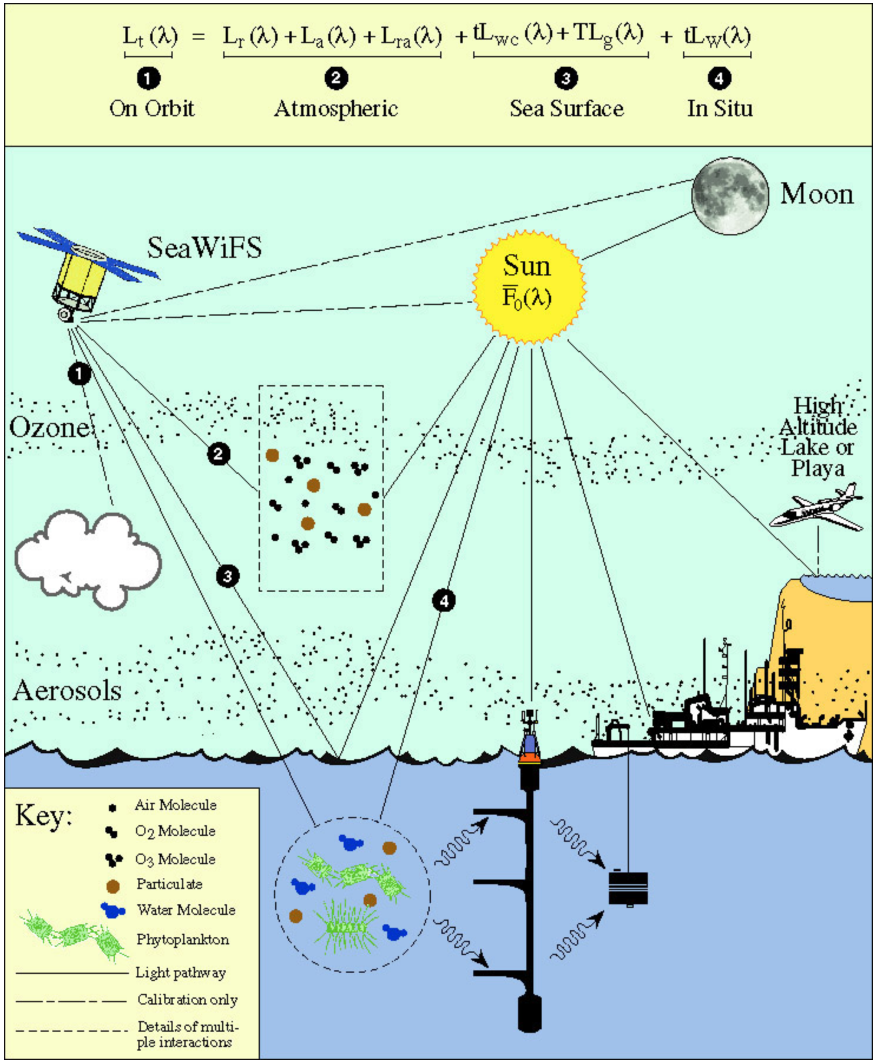
Internal Calibrator (IC)

Landsat Data Continuity Mission OLI Calibration

- Pre-Launch
  - 100 cm integrating sphere (NIST traceable)
    - Transfer sphere calibrated at NIST
    - Both spheres monitored with transfer radiometers
  - Solar Diffuser BRDF characterization (NIST traceable)
  - Heliostat-based transfer to orbit test
  - Polarization Sensitivity & Stray Light Tests
- On-Orbit
  - Solar diffusers
    - Weekly primary diffuser
    - Twice yearly pristine diffuser
  - Lamps
    - Daily working lamps
    - Twice-monthly reference lamps
    - Twice yearly pristine lamps
  - Lunar observations monthly (~7 ° phase)
  - Vicarious measurements ~ monthly
  - Desert sites ~2/monthly

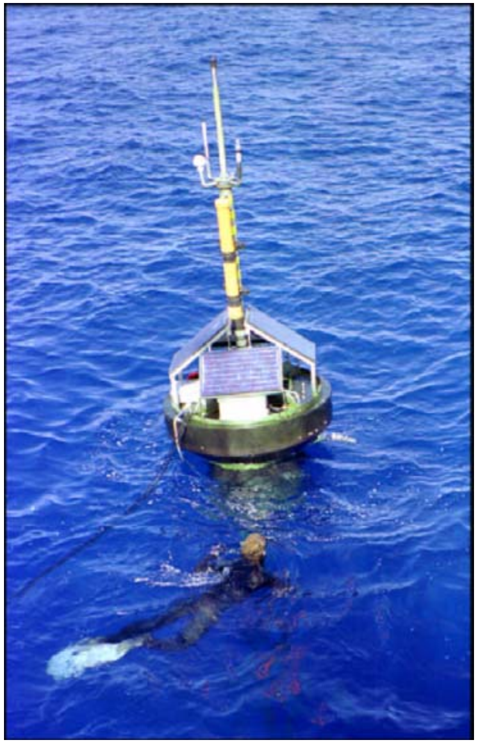
SeaWiFS Calibration: the Ocean Color Cal/Val Paradigm

- Pre-launch laboratory
  - Linearity, T sensitivity, polarization sensitivity, spectral response functions, RVS function, bright target response, et al.
- Post-launch on-orbit
  - Daily solar diffuser views to track short t sensitivity variations
  - Monthly lunar views at ~7° lunar phase to track long t sensitivity variations
  - Daily cal pulse to track instrument electronics stability
  - Vicarious cal gain adjustments using MOBY off Lanai, HI



SeaWiFS On-orbit Calibration: System + Algorithm

- MOBY (marine optical buoy) for bands 1-6
  - In-water system moored off Lanai in “clear water”
  - MOBY time series since 1996
  - Hyperspectral data over VNIR
  - Calibration and characterization
    - Characterized using NIST’s travelling SIRCUS
    - NIST-traceable cals pre- and post-deployment
    - Monthly measurements with stable, diver-deployed lamps verified using NIST designed radiometers
    - Daily scans of 3 internal sources



- Bands 7 (765nm) and 8 (865nm) to determine aerosol plus Rayleigh-aerosol term in LT
- B7 adjusted to match marine haze model and B8 aerosol radiances over open ocean.
- Aerosol type and single scattering reflectances for VIS/NIR bands derived from model.
- Aerosol type and 865 nm radiances (aerosol amount) used to determine aerosol plus Rayleigh-aerosol term for VIS bands
- No vicarious calibration correction applied to band 8

Lessons Learned (I)

- Having a science team (in addition to project team) supported several years before and after launch is essential in achieving mission overall success
  - Design requirements (spectral, spatial, and radiometric), SRR, PDR, CDR
  - Pre-launch calibration and characterization
  - Post-launch validation
- Establishing good communications is critical
  - Seamless interface among all parties; trusting working relationship
- A dedicated calibration team, in support of project, needs to work closely with the contractor and the science team for the instrument pre-launch calibration and in planning for post-launch validation
  - Independent calibration and verification
  - Vigilance and knowledge
  - Involving NIST in a review and perhaps pre-launch validation capacity
- Calibration/characterization effort needs to be sustained over the entire mission
  - Track/correct sensor on-orbit changes

Lessons Learned (II)

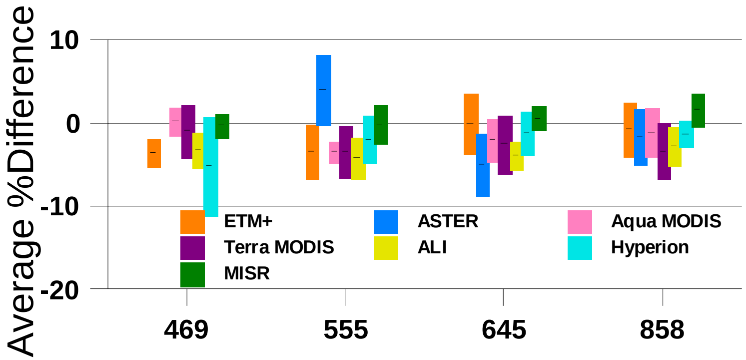
- Calibration standards and traceability
  - Calibration methodologies/approaches (NIST involvement)
  - Unbroken SI traceable calibration chain (pre- and post-launch)
- Calibration plan and test procedure
  - Extensive and complete review by cal team (including NIST and peer cal experts)
  - GSE qualification/characterization
- A complete uncertainty (error budget) analysis
  - Component level to system level
- Comprehensive sensor calibration and characterization activities
  - Component-level; sub-system level; end-to-end test
  - “Test as It Flies” under simulated on-orbit operating conditions
- Eliminate sensor “undesirable features” if possible
  - Non-physics based algorithm correction won’t work (more characterization effort)
  - Examples from MODIS

Lessons Learned (III)

- Documentation and data records
  - Sensor test data, tools, and results
  - Algorithm reviews (L1 in EOS-speak, SDR in NPP/NPOESS-speak)
  - Progress report and instrument status update for community reference
  - Technical memos, conference presentations, peer reviewed journals on topics of instrument operation and calibration, and lessons learned

CLARREO as a Calibration Benchmark for Future Earth Observing Missions

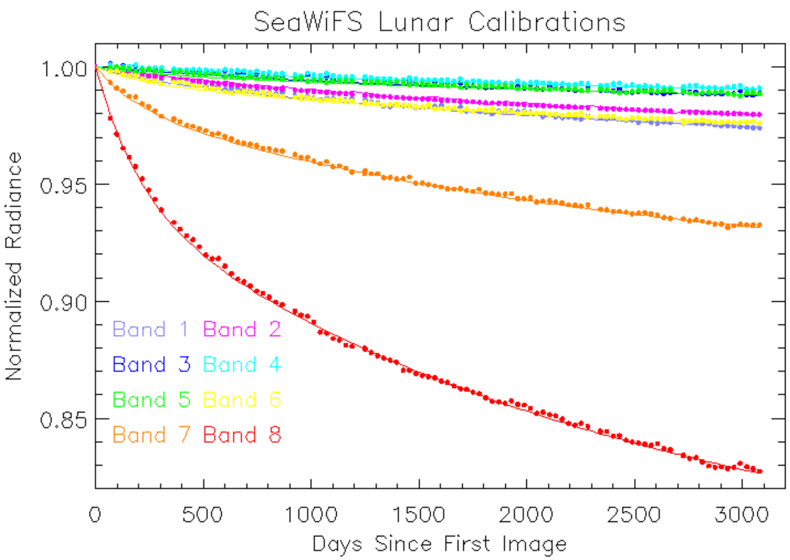
- Vicarious calibration
  - To date, the majority of satellite remote sensing instrument comparisons have been *comparisons and not calibrations or cross-calibrations*.
    - Comparisons serve the important purpose of checking instrument relative scales except for those instruments with non-existent or malfunctioning cal. systems.
    - Usually comparison agreements are within the combined uncertainties of the instruments' measurements.
    - Therefore, comparisons are not sufficiently rigorous to be used to validate (or possibly change) instruments' calibration coefficients.
  - Rule of thumb for laboratory calibrations is to use a reference or test instrument which has a 3x or lower measurement uncertainty. A similar goal should be adopted for on-orbit instrument comparisons.
  - CLARREO on-orbit measurement uncertainties would provide the high accuracy/low uncertainty to confidently validate satellite instrument calibrations.



V/C Method	Expected Uncertainty
Artificial Test Sites	2.8% (reflectance) 1.8 % (radiance)
Moon	2%

CLARREO as a Calibration Benchmark for Future Earth Observing Missions

- CLARREO measurements of the Moon in the VIS through SWIR will increase the viability of using the Moon for radiometric calibration
  - Current status:
    - Vis/nir/swir lunar irradiance model absolute accuracy is 5 to 10%
    - Dependence of irradiance model on lunar phase being characterized



SeaWiFS: Monthly lunar views near or at ±7° lunar phase enables tracking of on-orbit responsivity to <0.1% over the SeaWiFS mission.

MODIS: Monthly lunar views near or at ±55° lunar phase

  - High accuracy radiometric measurements of Moon by CLARREO
    - Due diligence needed to identify and quantify all uncertainties in using the Moon as an on-orbit calibration target

Summary

- CLARREO mission objective is to produce climate benchmarks through high accuracy, absolute on-orbit measurements
  - Measurement uncertainties require that the calibration SI traceability chain must be minimized
- Lessons from other Earth-observing sensors
  - Instrumentation and approaches are needed to establish absolute SI on-board
  - A comprehensive calibration plan and associated test procedures are needed before any calibration and characterization measurements
  - For the reflected solar region, significant improvement over current calibration uncertainty qualifies CLARREO to be used as an on-orbit calibration standard for other research and operational instruments.
  - CLARREO lunar views make the Moon a potentially viable on-orbit target for instrument calibration and comparison